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MODEL OF SPACECRAFT ATOMIC OXYGEN AND SOLAR EXPOSURE MICROENVIRONMENTS*

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INTRODUCTION

Computer models of environmental conditions in Earth orbit are needed for the following reasons: (1) derivation of material performance parameters from orbital test data, (2) evaluation of spacecraft hardware designs, (3) prediction of material service life, and (4) scheduling spacecraft maintenance. To meet these needs, Boeing has developed programs for modeling atomic oxygen (AO) and solar radiation exposures. The models allow determination of AO and solar ultraviolet (UV) radiation exposures for spacecraft surfaces (1) in arbitrary orientations with respect to the direction of spacecraft motion, (2) over all ranges of solar conditions, and (3) for any mission duration. The models have been successfully applied to prediction of experiment environments on the Long Duration Exposure Facility (LDEF) and for analysis of selected hardware designs for deployment on other spacecraft.

The work on these models has been reported at previous LDEF conferences (refs. 1 through 5). Since publication of these reports, a revision has been made to the AO calculation for LDEF, and further work has been done on the microenvironments model for solar exposure.

OBJECTIVE

The objective of this report is to present the results of a revised calculation for AO exposure of LDEF experiments and to describe a newly developed microenvironments model for predicting solar exposure of spacecraft.

ATOMIC OXYGEN EXPOSURE

Primary Atomic Oxygen Model

Since 1986 Boeing has been developing predictive models for determining the exposure of a spacecraft surface to AO. The first program developed is referred to as the primary AO exposure

* Includes work done under NAS 1-19247, Task 8.

model. The primary model is used to determine the AO flux (atom/cm^2-s) and fluence (atoms/cm^2) to flat surfaces. The model includes the effects of thermal motion of ambient AO atoms and co-rotation of the atmosphere in addition to the ambient atmospheric density and the velocity of the spacecraft. The model treats noninterfering surfaces at arbitrary, but definite, orientations with respect to the direction of spacecraft motion. Orbit parameters and mission duration are defined by the user. The NASA MSIS-86 Model Atmosphere (ref. 6) is used to establish atmospheric densities as a function of time. Solar conditions required by the model atmosphere are input as functions of time.

Details of the primary model were presented at the First LDEF Post-Retrieval Symposium and at the LDEF Materials Workshop '91 (refs. 1,2) and its application to LDEF is reported in NASA CR 189627 (ref. 3). Following publication of reference 3, a revised prediction of AO fluences to LDEF experiments was completed. Results of the revised calculation are shown in Figure 1. The revision calculation differs from that given in reference 3 because of a correction made to the atmospheric co-rotation programming code. The actual differences between the two calculations is not large (3 to 4 percent) for leading surfaces of the spacecraft (rows 7, 8, 9, 10, and 11). For rows 12 and 1 on the side of the vehicle, the revised calculation shows an increase of about 25 percent relative to the previous calculation. A greater relative increase was seen on trailing edge rows 4 and 5, but the total fluence values for these rows are still very low. The total fluence values for rows 1, 2, and 3 are unchanged because fluence to these rows was dominated by the brief unplanned AO exposure during retrieval of the LDEF.

Atomic Oxygen Microenvironments Model

A second, more detailed AO exposure model has been developed over the last 2 years to account for interference, or shadowing of surfaces, by the three-dimensional structure of a spacecraft. This model, termed the "AO microenvironments model," also accounts for specular and diffuse reflectance from surfaces exposed to either primary or secondary impacts, and accounts for the potential of individual atoms to recombine on, or react with, the impacted surface. The secondary scattering processes are determined by a Monte Carlo routine which follows an individual particle until it either reacts on a surface or is scattered back into the ambient environment.

The microenvironments model is described in the proceedings of the LDEF Materials Workshop '91 (ref. 2) and the proceedings of the Second LDEF Post-Retrieval Symposium (ref. 4). Comparisons of observed effects of AO on materials flown on LDEF with results predicted by the microenvironments model are presented in references 4 and 5. The AO microenvironments model predicted exposure effects to within the uncertainty of the corresponding experimental measurements.

The model predictions are sensitive to the relative contribution of specular and diffuse scattering and to recombination efficiency. The surface property data we have used are estimates. We have made preliminary determinations of recombination efficiency for copper, silver oxide, gold, and anodized aluminum in the laboratory using calorimetric measurements. Further research is needed to establish the methodology for laboratory measurement of molecular reflective properties and recombination efficiency of spacecraft materials.

SOLAR RADIATION EXPOSURE

Solar radiation exposure of LDEF is reported in reference 7 which gives exposure in equivalent Sun hours for each surface of the LDEF vehicle. Like the AO exposure shown in Figure 1, the solar exposure data reported in reference 7 are limited to flat or convex, noninterfering surfaces. To overcome these limitations, Boeing has developed a "solar exposure microenvironments model" to account for shadowing and scattering of solar radiation caused by complex surface geometry. The model is similar to the "AO microenvironments model." The effects on solar exposure caused by any arbitrary surface size or shape may be modeled, including protrusions, indentations, and curvature. Figure 2 illustrates the effects on shadowing, specular reflection, and diffuse reflection of solar exposure of an indented surface.

The "solar microenvironments model" accounts for both direct and for Earth-reflected solar radiation. Entry times are randomly selected for solar ephemeral calculations. Satellite positions are determined using an orbital mechanics routine. For the selected position of the Sun, rays are traced to nodes on the spacecraft surface. The Monte Carlo routine follows individual rays as they reflect from surface to surface. Once a ray is either absorbed on a surface or is scattered back into the ambient environment, the process is repeated for another Sun position. Earth-reflected radiation is handled in a similar manner except that the source of Earth-reflected radiation is taken as a location on Earth determined by weighted-random selection. The attributes of the solar microenvironments model are summarized in Table 1.

Equivalent Sun hours exposure calculated by the Monte Carlo solar microenvironments model are shown on Table 2 compared with results reported for LDEF in reference 7. The results reported in reference 7 are based on a deterministic analysis. Deterministic analyses of solar exposure are limited in application to simple geometries and generally do not account for reflected radiation and shadowing. The data reported in reference 7 are valid for exposure of noninterfering, flat planar surfaces. The Monte Carlo calculation was applied to the same geometry. Even though the procedures used for the two calculations are totally different, results are in satisfactory agreement for the six locations on LDEF for which comparisons were made. However, the comparison is for the flat surfaces. Routines in the microenvironments program for shadowing and for scattering of radiation between surfaces must be verified by other means.

The solar microenvironments model has been used to predict solar exposure at the edge fold of a silverized/fluorinated ethylene propylene (FEP) thermal control blanket. The fold analyzed was at the trailing edge of Experiment tray D1. The blanket edge is identified in Figure 3. The most frequent azimuth of the Sun, visible from the experiment, tends to be west of the vehicle. This point is important in understanding the results calculated by the microenvironments program for exposure of the blanket edge.

The geometry of the blanket edge attachment is shown in Figure 4. Figure 5 shows how distance is defined. Distances shown in Figure 5 are measured first along the surface of the blanket and then continue along the aluminum frame of the experiment tray. The edge of the FEP blanket was designated as 45 millimeters. The origin (zero distance) for the measurements is a point on the flat, FEP-covered surface of the experiment tray. Points along the surface of the aluminum frame are at distances greater than 45 mm from the origin. The Sun at any randomly chosen time can be in any direction from an examined point (node) on the experiment surface as determined by solar ephemeral calculations. The Sun may not be visible from a node position. For aft-facing trays, the most frequently observed Sun directions tend to be aft (to the right for tray D1 as shown in Figure 4) of the tray surface normal because the path of the Sun tends to be overhead and is not always visible from the side of the vehicle. This causes the radius between distances of 20 to 30 mm along the FEP blanket to be the most directly exposed surface of the blanket. Also, reflections from the FEP side of the attachment notch would be directed toward the aluminum. Much less reflection from the aluminum to the FEP would be expected than from the FEP to the aluminum.

These expectations are verified by the results shown in Figure 6. The area of highest solar exposure corresponds to the radius of the blanket fold (from 20 to 30 mm). The area of highest incidence of reflected radiation is on the aluminum side of the edge notch (from 45 to 60 mm). Exposure of the surface between 0 and 20 mm is the same as between 74 and 100 mm as would be expected because these surfaces are flat and parallel, thus they always make the same angle with a ray from the Sun.

Figure 6 shows that the plotted results of the Monte Carlo calculation are jagged. This may be due in part to statistical variations. The selection of node spacing and the number of Sun positions for the test case may not have been optimum. Overall, the calculated exposures behave as expected. Even with the variations noted, the results would be accurate enough for many engineering uses. The model is new and improvements will be incorporated as they are identified. The test calculation shown in Figure 6 does not provide verification between observed and predicted exposure of the materials on LDEF because the effects of solar exposure on FEP materials are not readily quantified.

Another factor in estimating solar exposure effects should be noted. The model yields equivalent Sun hours of exposure, the same as the deterministic model (ref. 7). It is radiation in the vacuum UV range that significantly affects exposed materials. The intensity of UV radiation at wavelengths shorter than 1,800 Å in the solar spectrum is a function of solar activity (ref. 8). This variation can be taken into account in future versions of the Monte Carlo model.

Applications of the environmental models are listed in Table 3. The primary AO program has been the most widely used thus far. The new microenvironments programs will greatly extend the application range of the modeling work in the future. We are now working on more flexible spacecraft orientation routines which will facilitate the determination of materials exposures on spinning and maneuvering satellites.

CONCLUSIONS

The latest revision of the AO exposure calculation reported herein should be used for analysis of LDEF results. The newly developed solar exposure microenvironments model produces results that are consistent with the deterministic model for flat surfaces exposed in orbit. Solar exposures calculated for surfaces of complex geometry using the microenvironments model are consistent with expected radiation intensity and reflection patterns.

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Table 1. Solar exposure microenvironments model.

Monte Carlo calculation of solar exposure to complex spacecraft surfaces.
• Includes direct-solar and Earth-reflected radiation.
• Multiple scattering of radiation from surface to surface.
• Weighted-random selection of specular reflection, diffuse reflection, or absorption with probabilities dependent on surface properties.
• Flexible input allows modeling for long or short missions.
Precision proportional to square root of number of Sun and satellite position pairs.
Code is computationally intensive.

Table 2. Comparison of Monte Carlo and deterministic models for solar exposure.

Surface	Monte Carlo, Sun Hours	NASA CR-189554, Sun Hours	Difference, Percent
Space End	14,200	14,547	–2.4
Earth End	4,400	4,472	–1.6
Row 3	11,900	11,100	+7.2
Row 6	6,690	6,400	+4.5
Row 9	10,900	11,200	–2.7
Row 12	6,900	6,800	+1.5
			Standard Deviation 4.1

LDEF Mission 1,000 Sun Positions Earth Albedo = 0.246 Surface Grid: 10×10

Table 3. Applications of the environment models.

Atomic Oxygen Exposure
- LDEF
  - Fluence as a function of time by tray.
  - Thermal control blanket edge attachment, trays B7 and D11.
  - Angle bracket, tray F9.
  - Copper grounding straps.
  - Specimen cover plate for Experiment A0171.
  - Space-end tray clamp.
- Space Station *Freedom*
  - Fluence as a function of time and incidence angle.
- EOIM-3 Orbital Test
  - Indirect exposure experiment.
- TRMM—Tropical Rain Forest Measurement Mission
  - AO fluence for mission.

Solar Exposure
- LDEF
  - Comparison of Monte Carlo model with analysis by Berrios and Sampair.
  - Thermal control blanket edge attachment, trays D1 and C5.
- TRMM—Tropical Rain Forest Measurement Mission
  - UV exposure for mission.

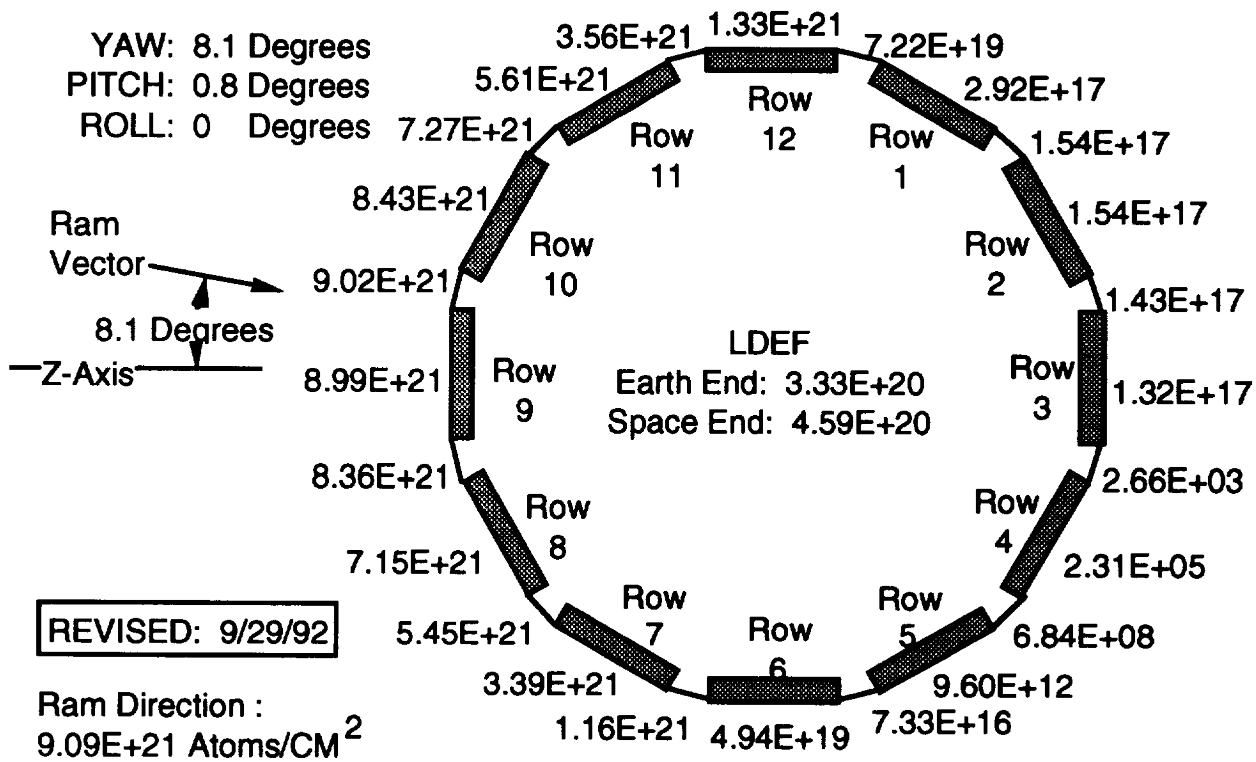

Figure 1. AO fluences at end of mission for all LDEF row, longeron, and end-bay locations including the fluence received during the retrieval altitude excursion.

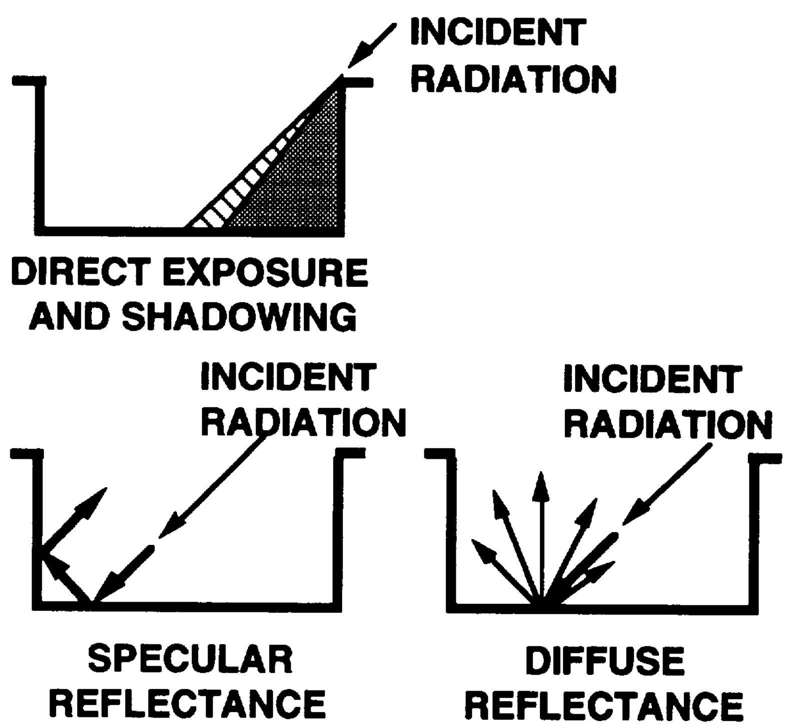

Figure 2. Effects of local geometry on solar exposure of spacecraft surfaces.

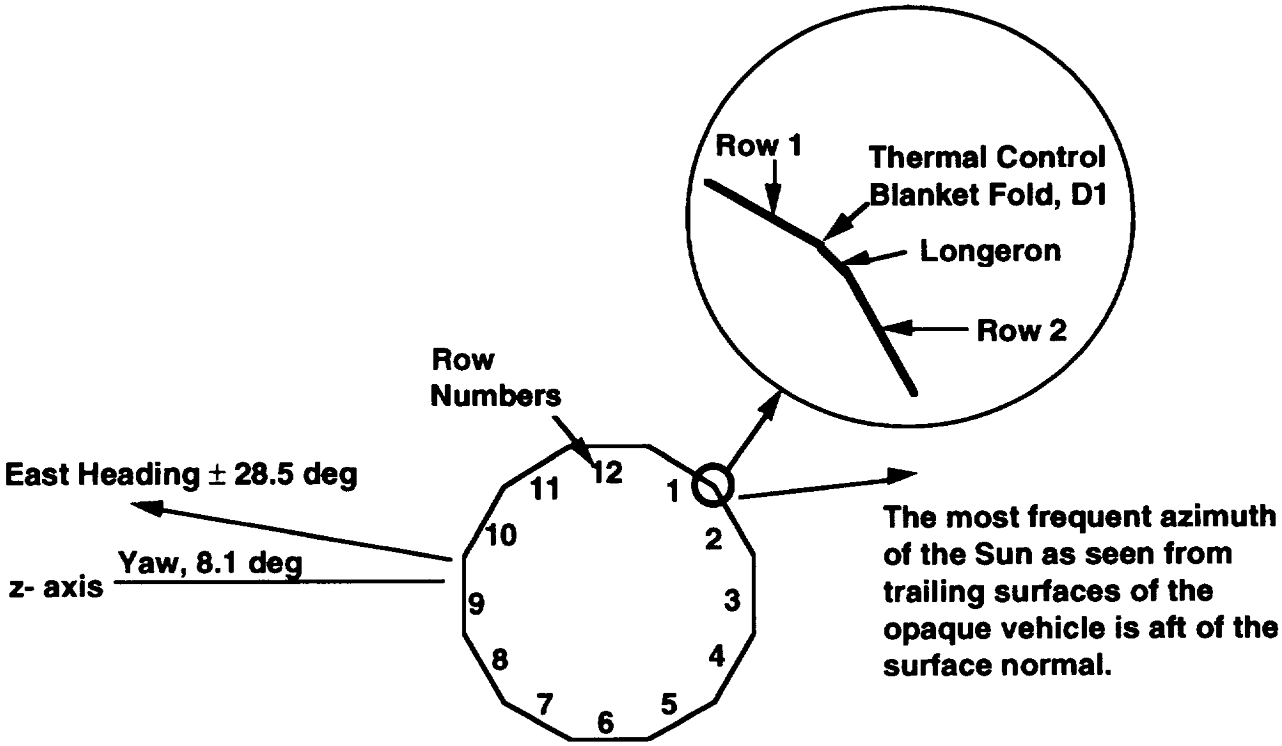

Figure 3. Location of the trailing side of LDEF Experiment tray D1.

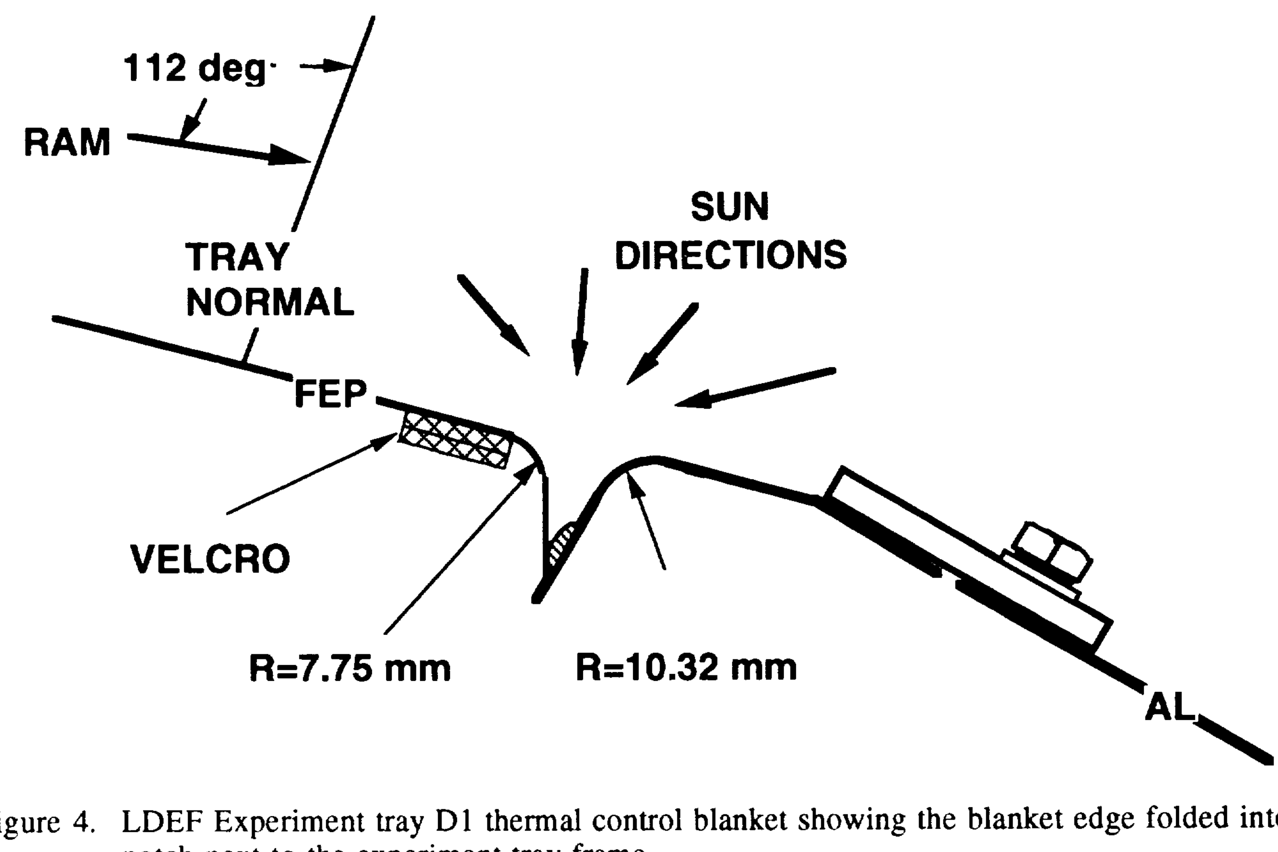

Figure 4. LDEF Experiment tray D1 thermal control blanket showing the blanket edge folded into a notch next to the experiment tray frame.

D1 near row 2 edge		Surface Properties		
		Specular	Diffuse	Absorption
	FEP Blanket	83%	10%	7%
	Aluminum	6%	60%	34%

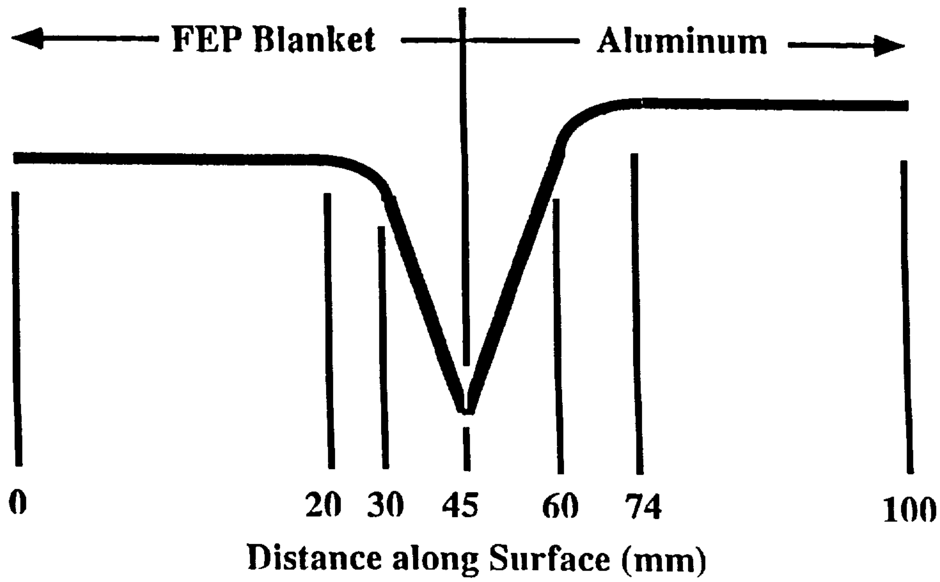

Figure 5. Definition of distance measurements for the microenvironments model study of the thermal control blanket edge fold, Experiment tray D1.

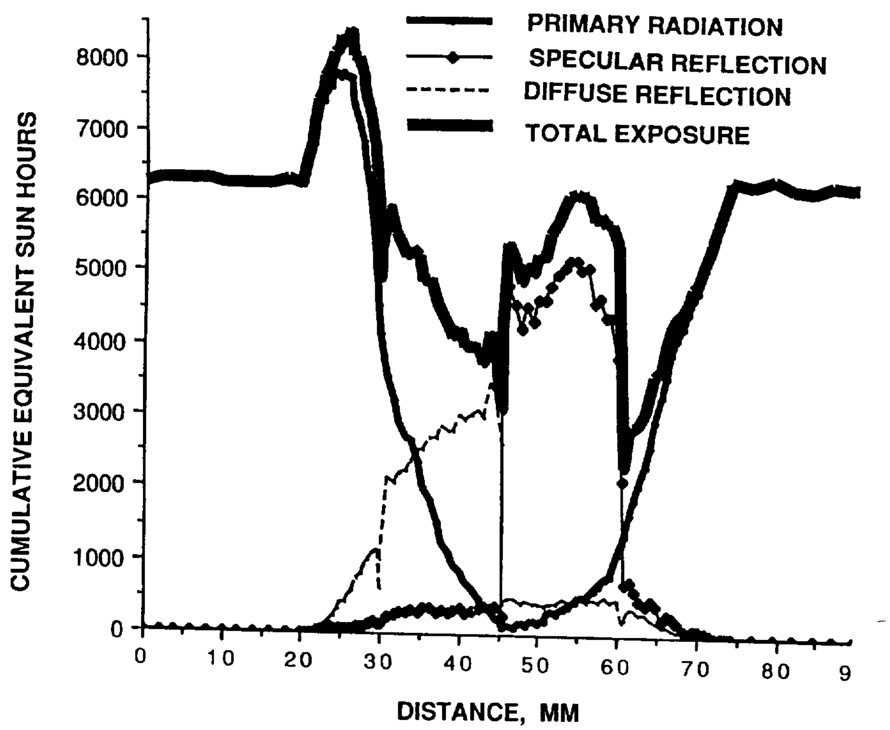

Figure 6. Calculated solar exposure for the Experiment tray D1, thermal control blanket fold.